I. FINAL REPORT FOR DE-FG52-03NA00076

Recipient – North Carolina State University
Name of Project – Nuclear Level Densities and γ-ray Strength Functions
Principal Investigator – G. E. Mitchell
Team Members –
Dr. Undraa Agvaanluvsan (post doctoral fellow)
Dr. Dugersuren Dashdorj (graduate student, then post doctoral fellow)
Steven Sheets – graduate student
Dr. Milan Krticka – Assistant Professor, Charles University, Prague, Czech Republic

II. DISTRIBUTION LIMITATION NOTICES

None

III. EXECUTIVE SUMMARY

Level densities and radiative strength functions are crucial for stewardship science, in particular for radiochemical studies. In addition, this information is key to understanding nucleosynthesis and thus very important for astrophysics. We utilized a method that derives simultaneously the nuclear level density and the radiative strength function for energy regions that are extremely difficult to study via other methods.

In heavy nuclei there is evidence for the systematic appearance of a low energy resonance in the radiative strength function (the so-called pygmy resonances). We have studied the same final nuclide (^{171}Yb) via different nuclear reactions and obtained the same energy and width for the low energy resonance. We also extended the method to lighter nuclei, including ^{56,57}Fe, $^{93-98}$Mo, and ^{116,117}Sn. For the iron and molybdenum isotopes an enhancement of the radiative strength function was observed at low energy. Subsequent measurements in iron appear to confirm this unusual effect. Our measurements in tin do not observe the enhancement, nor did any of the earlier measurements in heavy nuclei. The issue is still unsettled and is quite important for various aspects of neutron capture.

We also measured neutron induced γ-ray reactions on ^{48}Ti using the GEANIE array at LANSCE/WNR at Los Alamos National Laboratory. One key issue in understanding neutron induced reactions is determining the relative amount of preequilibrium and compound nuclear reaction processes. For some reactions the preequilibrium process dominates above 8-10 MeV neutron energy. We have focused on new ways to determine the relative amount of the two reaction processes.

IV. COMPARISON OF RESULTS WITH STATED GOALS

Our proposal goals were the measurement of level densities and radiative strength with an emphasis on extending the analysis method to lighter nuclei. We have results for 2 iron isotopes, 6 molybdenum isotopes, 2 tin isotopes and 2 ytterbium isotopes. In the process we not only exceeded our original goals, but also found a completely unexpected effect that has stimulated much additional work in this area.

We achieved our stated goal of measuring neutron induced reactions on ^{48}Ti, including reactions to eleven different final isotopes.

V. PROJECT ACTIVITIES

A Research

We studied the same final nucleus ^{171}Yb via two different nuclear reactions and obtained the same result for the energy and width of the pygmy resonance, thus confirming the reliability of the method in heavy nuclei.

We extended the analysis method to lighter nuclei and studied 2 iron isotopes and 6 molybdenum isotopes. In these nuclides we observed an enhancement of the radiative strength function at low energies. This effect was not observed in all earlier studies in heavy nuclei.

To examine the enhancement issue we then studied two tin isotopes and did NOT observe the enhancement. Subsequent measurements of the level density for ^{57}Fe agreed with our results. Two subsequent measurements of neutron capture on ^{56}Fe have obtained conflicting results. The enhancement issue is still unresolved.

We have measured neutron induced reactions on ^{48}Ti to 11 final nuclides and have performed extensive statistical model calculations. We conclude that preequilibrium effects are dominant for certain reactions (such as neutron inelastic scattering) above 8 to 10 MeV neutron bombarding energy.

B Personnel

The post doctoral fellow Undraa Agvaanluvsan was hired by the N division of Lawrence Livermore National Laboratory.

The student Dugersuren Dashorj received his Ph.D. from North Carolina State University for research at GEANIE and became a post doctoral fellow on this grant.

The graduate student Steven Sheets has continued his research on neutron capture and will defend his Ph.D. dissertation in early 2007. He will then be hired by Lawrence Livermore National Laboratory.

Assistant Professor Milan Krticka spent summers at Lawrence Livermore National Laboratory performig research into statistical γ-ray decay. He mainly applied statistical model codes that were developed at his home university – Charles University, Prague.

VI. PRODUCTS

A Publications

1. Radiative Strength Functions and Level Densities, A. Schiller, J.A. Becker, L.A. Bernstein, A. Voinov, M. Guttormsen, M. Hjorth-Jensen, J. Rekstad, S. Siem, G.E. Mitchell, and E. Tavukcu, *11th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics*, eds. J. Kvasil, P. Cejnar, and M. Krticka (World Scientific, Singapore, 2003), p. 432.

2. Thermodynamic Properties of ^{56}Fe, E. Tavukcu, J.A. Becker, L.A. Bernstein, M. Guttormsen, E. Melby, G.E. Mitchell, J. Rekstad, A. Schiller, and S. Siem, *Frontiers of Nuclear Physics*, eds. P. Fallon and R. Clark (AIP Conference Proceedings 656, Melville, New York, 2003), p. 136.

3. Average Nuclear Level Densities and Radiative Strength Functions in ^{56,57}Fe from Primary γ-ray Spectra, E. Tavukcu, J.A. Becker, L.A. Bernstein, P.E. Garrett, M. Guttormsen, G.E. Mitchell, J. Rekstad, A. Schiller, S. Siem, A. Voinov, and W. Younes, *Application of Accelerators in Research and Industry: Seventeenth International Conference*, eds. J.L. Duggan and I.L. Morgan (AIP Conference Proceedings 680, Melville, New York, 2003), p. 296.

4. Level Densities from Proton Resonances, U. Agvaanluvsan, G.E. Mitchell, M. Pato, and J.F. Shriner, Jr., *Application of Accelerators in Research and Industry: Seventeenth International Conference*, eds. J.L. Duggan and I.L. Morgan (AIP Conference Proceedings 680, Melville, New York, 2003), p. 321.

5. Level Densities in ^{56,57}Fe and ^{96,97}Mo, A. Schiller, E. Tavukcu, L.A. Bernstein, P.E. Garrett, M. Guttormsen, M. Hjorth-Jensen, C.W. Johnson, G.E. Mitchell, J. Rekstad, S. Siem, A. Voinov, and W. Younes, Phys. Rev. C **68**, 054326 (2003).

6. Level Densities and Radiative Strength Functions in ^{171}Yb and ^{170}Yb, U. Agvaanluvsan, M. Guttormsen, G.E. Mitchell, J. Rekstad, A. Schiller, and S. Siem, *XI International Seminar on Interactions of Neutrons with Nuclei, ISINN-XI* (Joint Institute of Nuclear Research, Dubna, Russia, 2004), p. 65.

7. Large enhancement of radiative strength for soft transitions in the quasicontinuum, A. Voinov, E. Algin, U. Agvaanluvsan, T. Belgya, R. Chankova, M. Guttormsen, G.E. Mitchell, J. Rekstad, A. Schiller, and S. Siem, Phys. Rev. Lett. **93**, 142504 (2004).

8. Level Densities and γ-ray Strength Functions in $^{170.171,172}$Yb, U. Agvaanluvsan, A. Schiller, J.A. Becker, L.A. Bernstein, P.E. Garrett, M. Guttormsen, G.E. Mitchell, J. Rekstad, S. Siem, A. Voinov, and W. Younes, Phys. Rev. **C70**, 054611 (2004).

9. ^{48}Ti(n,xnypz$\alpha\gamma$) reaction cross section using spallation neutrons for E_n = 1 to 20 MeV, D. Dashdorj, G.E. Mitchell, P.E. Garrett, U. Agvaanluvsan, J.A. Becker, L.A. Bernstein, J.R. Cooper, R.D. Hoffman, R. Macri, W. Younes, M. Devlin, N. Fotiades, and R.O. Nelson, Lawrence Livermore National Laboratory Technical Report UCRL-TR-209474 (2005).

10. Radiative strength function in $^{93-98}$Mo, M. Guttormsen, R. Chankova, U. Agvaanluvsan, E. Algin, L.A. Bernstein, F. Ingebretsen, T. Lönroth, S. Messelt, G.E. Mitchell, J. Rekstad, A. Schiller, S. Siem, A.C. Sunde, A. Voinov, and S. Odegard, Phys. Rev. **C71**, 044307 (2005).

11. Level Densities and Radiative Strength Functions, E. Algin, A. Schiller, A. Voinov, U. Agvaanluvsan, T. Belgya, R. Chankova, M. Guttormsen, M. Hjorth-Jensen, C.W. Johnson, G.E. Mitchell, J. Rekstad, and S. Siem, *World Year of Physics, Turkish Physical Society, 23rd International Physics Conference*, Mugla, Turkey, 2005, p. 447.

12. Soft resonances in hot nuclei, S. Siem, M. Guttormsen, E. Algin, U. Agvaanluvsan, T. Belgya, L.A. Bernstein, R. Chankova, G.E. Mitchell, J. Rekstad, A. Schiller, A.C. Sunde, N. Syed, and A. Voinov, Acta Polonica **B36**, 1093 (2005).

13. Improved level densities via identification of spurious levels, U. Agvaanluvsan, G.E. Mitchell, D. Dashdorj, C.M. Frankle, S.F. Lokitz, and J.F. Shriner, Jr., *International Conference on Nuclear Data*, ed. R.C. Haight, M.B. Chadwick, T. Kawano, and P. Talou, AIP Conference Proceedings 769, Melville, N. Y. (2005), p. 1164.

14. ^{48}Ti(n,xnypz$\alpha\gamma$) reaction cross section for neutron energies up to 250 MeV, D. Dashdorj, P.E. Garrett, J.A. Becker, L.A. Bernstein, J.R. Cooper, M. Devlin, N. Fotiades, G.E. Mitchell, R.O. Nelson, and W. Younes, *International Conference on Nuclear Data*, ed. R.C. Haight, M.B. Chadwick, T. Kawano, and P. Talou, AIP Conference Proceedings 769, Melville, N. Y. (2005), p. 1035.

15. Investigation of the radiative strength function, U. Agvaanluvsan, E. Algin, J.A. Becker, M. Guttormsen, G.E. Mitchell, S. Siem, A. Schiller, and A. Voinov, Nucl. Instrum. Methods Phys. Research B **241**, 180 (2005).

B Collaborations

Our primary collaboration was with scientists at the N division at Lawrence Livermore National Laboratory.

For the level densities and radiative strength function measurements we actively collaborated with the Nuclear Group at the Oslo Cyclotron Laboratory.

For the statistical decay we collaborated with a group headed by F. Becvar at the Charles University, Prague.

For the GEANIE measurements we actively with scientists at LANSCE/WNR, Los Alamos National Laboratory.